Joint Optimization of Power and Location in Full-Duplex UAV Enabled Systems

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***Abstract*—Unmanned Aerial Vehicles (UAVs) can be used as aerial base stations (BSs) for future small cells. They can increase the spectral efficiency of the small cells due to their higher probability to have line-of-sight connections and their mobility as a BS. In this paper, in order to show the effectiveness of using Full-Duplex (FD) technology in UAV networks, we consider a UAV equipped with FD technology (FD-UAV) with imperfect self interference cancellation as an aerial BS that serves both uplink (UL) and downlink (DL) users simultaneously in a small cell network. We aim to maximize DL sum-rate, whilst prescribing a certain quality of service for UL users, by optimizing the location of FD-UAV and available resources. The problem is non-convex, so we propose an iterative method by exploiting the difference of convex functions programming to jointly optimize transmission power of users, FD-UAV location and FD-UAV transmission power. Simulation results are illustrated to show the effectiveness of the proposed method for FD-UAV in comparison with ground BS, in both FD and half-duplex modes.**

***Index Terms*—Full-Duplex (FD), Unmanned Aerial Vehicle (UAV), Power Allocation, Location Optimization.**

I. Introduction

In future wireless networks, dealing with massive data and multiple connections are two of the key challenges. Unmanned Aerial Vehicles (UAVs) can be used as a promising solution for densely deployed small cells and can reduce the pressure on the ground networks [1], [2]. Using base stations (BSs) mounted on UAVs is a promising new evolution of wireless networks for providing high data rates and increasing the coverage area because of their line-of-sight (LoS) communication with ground users [3]–[5]. In addition, ground BSs have fixed locations while UAVs can change their locations and adapt themselves with environment dynamics. UAVs can be used in many applications such as provisioning bandwidth to disaster-stricken areas, covering suburban area networks, traffic monitoring and rescue operations. Moreover, employing Full-Duplex (FD) communication can double the link throughput in comparison with their traditional Half Duplex (HD) counterparts by simultaneous data transmission and reception in the same frequency band [6]–[8]. Recently, FD communication has been used in many applications in wireless systems [9]. However in such systems, self interference (SI) limits the performance level and therefore, SI cancellation (SIC) is a critical challenge [10].

One of the most useful applications of UAVs is to deploy them as a relay in cellular systems [1], [11]. Authors in [12] consider UAVs as aerial relays in the sky to provide multi-hop wireless connection between two distant users that have non-line-of-sight (NLOS) connection. The authors maximize the throughput by jointly optimizing UAV transmit power and trajectory. In [13] a FD-UAV is considered as a decode and forward relay. The authors jointly optimize source and relay transmit power and the trajectory of UAV to minimize network's sum outage probability. Authors in [14] consider a FD-UAV as a relaying system and apply decode and forward strategy to maximize instantaneous data rate by joint design of beamforming and power allocation. Authors in [15] consider a UAV as a relay-assisted node in a D2D wireless power and information transfer system. The authors develop a real-time resource allocation algorithm by jointly optimizing the energy harvesting time and power control for considered D2D pairs in order to energy efficiency maximization.

Another useful application of UAVs is utilizing them as aerial BSs [16]. Deployment of practical recharging solutions and optimization of power consumption for UAVs are important challenges in this application [3]. Due to UAVs' ability to move in three dimensional space, in comparison with ground BSs, they have unrestricted location options and can move to cover more users, while ground BSs have much less location options and are fixed [1]. Authors in [17] introduce UAVs as a solution for deploying dense networks by considering them as aerial BSs and assume coexistence of UAVs and ground BSs. The authors find optimal position of UAVs and associating users to ground BS or UAVs to maximize user satisfaction with provided data rates. In [18] a new hybrid network architecture is proposed where a UAV is employed as a aerial BS to offload data for cell edge users by flying cyclically along the cell edge. The minimum throughput of all downlink (DL) users is maximized by jointly optimizing the user partitioning, bandwidth and trajectory. The authors assume that the spectrum is shared between the UAV and the ground BS. In [19] a power efficient wireless sensor network is investigated, where a UAV is considered as a flying BS to communicate with DL sensor nodes. The authors minimize the total power consumption of UAV while considering the required transmission rate of DL. In addition, they jointly optimize scheduling scheme, power allocation and UAV trajectory. Authors in [20] study the network performance improvement in term of quality of service (QoS) by minimizing the average distance between UAV and users. They propose a distributed algorithm and prove its convergence. The authors in [21] investigate an uplink (UL) power control for UAV assisted network and assume that one UAV serves UL users. The authors aim to minimize the sum UL power, while considering the minimal rate demand by optimizing the altitude, UAV's location, power of users, antenna beamwidth and bandwidth.

As mentioned above, two important applications of UAVs are employing them as relay and BS. Both FD and HD modes are investigated in relay systems, while in cellular systems, just HD-UAVs are investigated and FD mode is not considered. In HD mode, UAVs serve UL or DL users, while in FD mode, both UL and DL users can be served simultaneously and this can increase the network capacity, considerably. The importance of employing FD technology in ground BSs is addressed in [22] where resource allocation problem is investigated, considering co-channel and SI.

According to the advances in FD transmission and advantages of UAVs in comparison with ground BSs, employing FD-UAVs as a flying BSs can be a promising candidate for next generations of cellular networks. Hence, in this paper, we introduce a network utilizing a FD-UAV as an aerial BS to serve both DL and UL cellular users in the same frequency band and the same time. We assume that FD is enabled at the BS with imperfect SIC while users can only operate in HD mode due to the hardware limitations. Since DL and UL transmissions coexist in this setting, co-channel interference between UL and DL users and SI have to be considered, and previous solutions in the literature cannot optimize the system performance. In this paper by considering practical assumptions, the sum-rate of DL users is maximized whilst prescribing a certain minimum requirement for UL users by jointly optimizing UAV location, UAV transmission power and the transmission power of users (In this paper, FD-UAV location means FD-UAV latitude and longitude). The optimization problem is non-convex, therefore, a successive convex approximation algorithm is developed by leveraging D.C. programming (Difference of Convex functions). We evaluate the performance of FD-UAV and compare the results with ground BS in both FD and HD modes to show the effectiveness of FD-UAVs as flying BSs. The main contributions of this paper are as follows:

- FD-UAV is considered as an aerial BS to serve both DL and UL users in the same frequency band and the same time, in order to maximize DL sum-rate while considering a certain QoS for UL users.
- The transmission power of users, UAV location (latitude and longitude) and UAV transmission power are jointly optimized, considering co-channel interference and SI.
- The performance of proposed system is compared with that of ground BSs, in both FD and HD modes.

The rest of this paper is organized as follows: We describe the system model and problem formulation in section II. We propose an iterative method to jointly optimize the transmission power of users and UAV location and transmission power in section III. Simulation results are presented and discussed in section IV and finally paper is concluded in section V.

II. System Model and Problem Formulation

Consider a UAV-enabled wireless communication system with a FD-UAV deployed as an aerial BS to serve cellular users. The FD-UAV is located at $\underline{y} = (y(1), y(2), H)$ in three dimensional space with N UL users which are located at $\underline{x_n} = (x_n(1), x_n(2), x_n(3)), n = 1, .., N$ and N DL users which are located at $\underline{z_n} = (z_n(1), z_n(2), z_n(3))$. In order to consider the worst case scenario for interference between UL and DL users, we assume that the number of UL and DL users are equal, i.e., in each channel, there are DL and UL users and they work in the same frequency band. In addition, we consider outdoor users in rural areas and assume that channel links are flat fading and remain unchanged in the scheduling process. The channel between UAV and the n^{th} UL user, the channel between UAV and the n^{th} DL user and the channel between the n^{th} UL and DL users are $\frac{h_u}{D_{y-x_n}^{\alpha_u}}$, $\frac{h_d}{D_{y-z_n}^{\alpha_d}}$ and $\frac{h_g g}{D_{z_n-x_n}^{\alpha_g}}$, respectively, where h_u, h_d and h_g are the channel power gains at the reference distance ($1m$) and g is the fading coefficient. Moreover, $D_{y-x_n} = \left\|\underline{y} - \underline{x_n}\right\| = \sqrt{(y(1) - x_n(1))^2 + (y(2) - x_n(2))^2 + (H - x_n(3))^2}$. In addition, α_u, α_d and α_g are the path-loss exponents for ground to air, air to ground and ground to ground communication, respectively (Fig. 1). The path-loss model for pico-cell environment is used as given in [23]. At $2GHz$ frequency, the LOS and NLOS path-losses for BS to users are given as follows:

$$\begin{array}{l} L_{BStoUser}^{LOS}[dB] = 32.9 + 20.9\log_{10}(d) \\ L_{BStoUser}^{NLOS}[dB] = 41.1 + 37.5\log_{10}(d) \end{array} \quad (1)$$

In addition, the LOS and NLOS path-losses for user to user are given as:

$$\begin{array}{l} L_{UsertoUser}^{LOS}[dB] = 38.45 + 20\log_{10}(d), d \leqslant 50 \\ L_{UsertoUser}^{NLOS}[dB] = 55.78 + 40\log_{10}(d), d > 50 \end{array} \quad (2)$$

where d is the distance in meter.

For the sake of simplicity and without loss of generality, we assume that each user is equipped with an omnidirectional antenna with unit gain and FD-UAV is equipped with directional antenna with an adjustable beamwidth. The azimuth and elevation half-power beamwidth of FD-UAV are equal and denoted by $2\Theta \in (0, \pi)$. The antenna gain in θ and φ directions (azimuth angle and elevation angle, respectively) can be modeled as [24]:

$$G = \begin{cases} \frac{G_0}{\Theta^2} & \text{if } 0 \leqslant \theta \leqslant \Theta \text{ and } 0 \leqslant \varphi \leqslant \Theta \\ g_0 \approx 0 & otherwise, \end{cases} \quad (3)$$

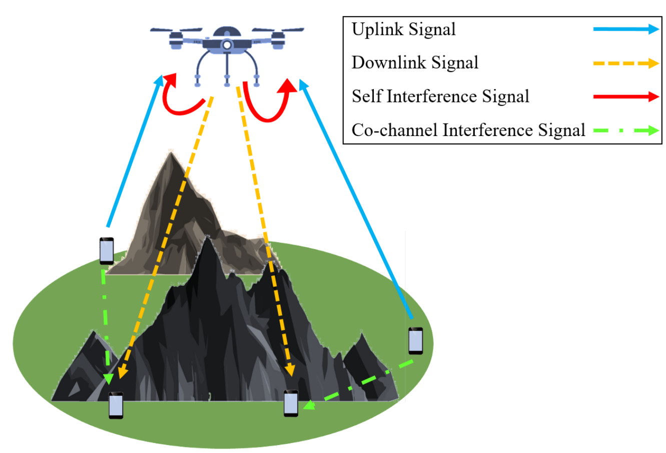

Fig. 1. System model

where $G_0 \approx 2.2846$ and g_0 shows the channel gain outside the antenna beamwidth.

The main problem of enabling FD is SI. To model this, we consider FD-UAV with imperfect SIC with residual SI to power ratio of β, i.e., if FD-UAV transmits data with the power of P_n^{UAV}, the residual SI is βP_n^{UAV} and the parameter β determines the amount of SIC; when $\beta = 1$, there is no SIC, while for $\beta = 0$ the SIC is perfect. In addition, we assume that there are N frequency bands and channel allocation is predetermined. In each channel, FD-UAV communicate with one UL and one DL user, simultaneously. In this case, the received signal to interference plus noise ratio (SINR) at FD-UAV and SINR at the n^{th} DL user can be expressed as (4) and (5), respectively:

$$\Gamma_n^{UL} = \frac{P_n^{UE} D_{y-x_n}^{-\alpha_u} h_u G}{\sigma_N^2 + \sigma_I^2 + \beta P_n^{UAV}}, \tag{4}$$

$$\Gamma_n^{DL} = \frac{P_n^{UAV} D_{y-z_n}^{-\alpha_d} h_d G}{\sigma_N^2 + \sigma_I^2 + P_n^{UE} D_{x_n-z_n}^{-\alpha_g} h_g g}, \tag{5}$$

where P_n^{UE} is the transmit power of the n^{th} UL user at the n^{th} channel, P_n^{UAV} is the transmit power of FD-UAV in the n^{th} channel, β models SIC at FD-UAV, σ_N^2 is the noise power and σ_I^2 models the interference from other cells that may exist. For simplicity we assume $\sigma^2 = \sigma_N^2 + \sigma_I^2$. Moreover, we should mention that the channel between UAV and ground users depends on antenna gain and half-power beamwidth (G and Θ), location of users (x_n or z_n), channel power gain at reference distance (h_u or h_d), path-loss exponent (α_u or α_d), and finally the location and altitude of UAV (D_{y-x_n}).

Now, UL and DL transmission rates for the n^{th} channel are given, respectively, by (6) and (7):

$$R_n^{UL} = w\log_2\left(1 + \Gamma_n^{UL}\right), \tag{6}$$

$$R_n^{DL} = w\log_2\left(1 + \Gamma_n^{DL}\right), \tag{7}$$

where w is the bandwidth of each frequency channel.

In order to cover all users, we should calculate the the FD-UAV altitude. Therefore, we assume a predetermined value for FD-UAV half-power beamwidth, i.e., $\Theta = \Theta_0$, then we calculate the FD-UAV altitude as:

$$\begin{gathered} H_0 = \max\left\{\frac{\max(D_{y-x_n})}{\tan\Theta_0}, \frac{\max(D_{y-z_n})}{\tan\Theta_0}\right\}, \\ H_L \leqslant H_0 \leqslant H_U. \end{gathered} \tag{8}$$

By assuming practical limits, the altitude of FD-UAV should be bounded between H_L and H_U. If the altitude of FD-UAV becomes lower than H_L, we set its value equal to H_L, and if it becomes more than H_U, we set its value equal to H_U. This may cause some users become out of coverage of that specific FD-UAV and other UAV should cover them in a cellular network.

We aim to maximize the sum-rate of DL transmission while considering a certain QoS for UL transmission rate by optimizing the location of FD-UAV and the transmit power of FD-UAV and users. The optimization problem can be represented as follows:

$$\begin{array}{ll} \max\limits_{P_n^{UAV}, P_n^{UE}, \underline{y}} & \sum\limits_{n=1}^{N} w\log_2\left(1 + \Gamma_n^{DL}\right) \\ s.t. & w\log_2\left(1 + \Gamma_n^{UL}\right) \geqslant R_{\min} \\ & \sum\limits_{n=1}^{N} P_n^{UAV} \leqslant P_{max}^{UAV} \\ & P_n^{UAV} \geqslant 0 \\ & P_n^{UE} \leqslant P_{max}^{UE}, \end{array} \tag{9}$$

where R_{min} is the minimum transmission rate considered for UL transmission, P_{max}^{UE} is the maximum transmit power of each user and P_{max}^{UAV} is the overall transmit power of FD-UAV.

III. Joint Power and Location Optimization

We aim to jointly optimize the location of FD-UAV and transmission power of FD-UAV and users to maximize sum-rate of DL, while guaranteeing a certain QoS for UL transmission rate.

Now, by calculating the FD-UAV altitude, we would like to solve the optimization problem (9), which can be rewritten as:

$$\max_{P_n^{UAV}, P_n^{UE}, \underline{y}} \sum_{n=1}^{N} w\log_2\left(1 + \Gamma_n^{DL}\right) \tag{10a}$$

$$s.t. \frac{\left(2^{\frac{R_{\min}}{w}} - 1\right)\left(\sigma^2 + \beta P_n^{UAV}\right)}{D_{y-x_n}^{-\alpha_u} h_u G} \leqslant P_n^{UE} \leqslant P_{max}^{UE} \tag{10b}$$

$$\sum_{n=1}^{N} P_n^{UAV} \leqslant P_{\max}^{UAV} \tag{10c}$$

$$P_n^{UAV} \geqslant 0. \tag{10d}$$

Feasibility of optimization problem (10) is presented in Appendix A. Regarding the optimal solution of optimization problem (10), we have the following lemma.

Lemma 1: *To maximize the DL sum-rate, for the optimal solution at least one constraint in optimization problem* (10) *holds with equality, i.e., at least one user or the FD-UAV must transmit with the maximum power.*

Proof: See Appendix B

In order to consider power consumption, we set a minimum value for the transmit power of users and change the constraint to the equality. Moreover, the upper bound for users' power is applied to the power of FD-UAV as follows:

$$\begin{array}{ll} \max\limits_{P_n^{UAV}, \underline{y}} & \sum\limits_{n=1}^{N} w\log_2\left(1 + \Gamma_n^{DL}\right) \\ s.t. & \frac{\left(2^{\frac{R_{\min}}{w}} - 1\right)\left(\sigma^2 + \beta P_n^{UAV}\right)}{D_{y-x_n}^{-\alpha_u} h_u G} = P_n^{UE} \\ & \sum\limits_{n=1}^{N} P_n^{UAV} \leqslant P_{\max}^{UAV} \\ & 0 \leqslant P_n^{UAV} \leqslant \frac{1}{\beta}\left(\frac{P_{max}^{UE} D_{y-x_n}^{-\alpha_u} h_u G}{\left(2^{\frac{R_{\min}}{w}} - 1\right)} - \sigma^2\right). \end{array} \tag{11}$$

By substituting P_n^{UE} in the problem (11), the first constraint is satisfied and the problem (11) changes as:

$$\begin{aligned} \min_{P_n^{UAV},\underline{y}} \quad & \left(-\sum_{n=1}^{N} w\log_2\left(1+A\right)\right) \\ s.t. \quad & \sum_{n=1}^{N} P_n^{UAV} \leqslant P_{\max}^{UAV} \\ & 0 \leqslant P_n^{UAV} \leqslant \frac{1}{\beta}\left(\frac{P_{max}^{UE} D_{y-x_n}^{-\alpha_u} h_u G}{\left(2^{\frac{R_{\min}}{w}}-1\right)} - \sigma^2\right), \end{aligned} \tag{12}$$

where $A = \frac{P_n^{UAV} D_{y-z_n}^{-\alpha_d} D_{y-x_n}^{-\alpha_u} h_d h_u G^2}{h_u D_{y-x_n}^{-\alpha_u} G\sigma^2 + \left(2^{\frac{R_{\min}}{w}}-1\right)(\sigma^2+\beta P_n^{UAV}) h_g g D_{x_n-z_n}^{-\alpha_g}}$.

The problem is non-convex, hence, a closed form solution is not known for it. Due to the fact that the sum-rate is a logarithmic function of SINR, this function can be rewritten as the difference of two logarithmic functions. Therefore, the sum-rate can be written as the difference of two convex functions. As a consequence, we develop a successive convex algorithm by leveraging the D.C. programming [25]. Therefore, the optimization problem (12) can be rewritten as a D.C. function, i.e., $f = g - h$. The D.C programming approximates f by $\widetilde{f} = g - \widetilde{h}$, where $\widetilde{h}$ is the first order Taylor's series approximation of h [26].

To solve the optimization problem (12), at first we assume that the location of FD-UAV is fixed and find the suboptimal value of FD-UAV transmission power, using D.C. programming. For simplicity, we replace $2^{\frac{R_{\min}}{w}} - 1$ by R^*, i.e., $R^* = 2^{\frac{R_{\min}}{w}} - 1$. We consider $P_n^{UAV(0)}$ as initial value and set $k = 0$. In addition, we define an auxiliary function $\widehat{g}_1\left(P_n^{UAV(k)}\right)$ as follows:

$$\begin{aligned} &\widehat{g}_1\left(P_n^{UAV(k)}\right) \triangleq \\ &-\sum_{n=1}^{N} \log_2\left(D_{y-x_n}^{-\alpha_u} h_u G\sigma^2 + (R^*)\left(\sigma^2+\beta P_n^{UAV}\right) h_g g D_{x_n-z_n}^{-\alpha_g}\right. \\ &\left.+P_n^{UAV} D_{y-z_n}^{-\alpha_d} D_{y-x_n}^{-\alpha_u} h_d h_u G^2\right) \\ &+\sum_{n=1}^{N} \log_2\left(D_{y-x_n}^{-\alpha_u} h_u G\sigma^2 + (R^*)\left(\sigma^2+\beta P_n^{UAV(k)}\right) h_g g D_{x_n-z_n}^{-\alpha_g}\right) \\ &+\sum_{n=1}^{N} \frac{(R^*)(\beta) h_g g D_{x_n-z_n}^{-\alpha_g}\left(P_n^{UAV} - P_n^{UAV(k)}\right)\Big/\ln 2}{D_{y-x_n}^{-\alpha_u} h_u G\sigma^2 + (R^*)\left(\sigma^2+\beta P_n^{UAV(k)}\right) h_g g D_{x_n-z_n}^{-\alpha_g}}. \end{aligned} \tag{13}$$

Then, we solve the optimization problem (14).

$$\begin{aligned} P_n^{UAV(k+1)} = \quad & \arg\min_{P_n^{UAV}} \widehat{g}_1\left(P_n^{UAV(k)}\right) \\ s.t. \quad & \sum_{n=1}^{N} P_n^{UAV} \leqslant P_{\max}^{UAV} \\ & 0 \leqslant P_n^{UAV} \leqslant \frac{1}{\beta}\left(\frac{P_n^{UE} D_{y-x_n}^{-\alpha_u} h_u G}{R^*} - \sigma^2\right). \end{aligned} \tag{14}$$

Subsequently, we set $k = k+1$. This procedure is repeated until the convergence or for a predefined number of iterations. This procedure is represented in Algorithm 1. The major complexity of Algorithm 1 lies in solving the problem (14). The complexity of solving problem (14) by using the standard interior point method is $\mathcal{O}(I_p N^3)$ [27] where N and I_p denote the number of users and the total number of iterations of Algorithm 1, respectively.

Algorithm 1: Optimizing power of FD-UAV

1 Initialize $P_n^{UAV(0)}$ and set $k = 0$ (iteration number).
2 **Repeat**
3 Define an auxiliary function $\widehat{g}_1\left(P_n^{UAV(k)}\right)$ as (13).
4 Solve the optimization problem (14).
5 $k \leftarrow k+1$
6 **Until** the sequence $\left\{\widehat{g}_1\left(P_n^{UAV(k)}\right)\right\}$ converges.

Now we assume that the transmission power of FD-UAV is fixed and we find the suboptimal location of the FD-UAV. We consider $\underline{y}^{(0)}$ as the initial value and set $i = 0$. Moreover, we define an auxiliary function $\widehat{g}_2\left(\underline{y}^{(i)}\right)$ as follows:

$$\begin{aligned} &\widehat{g}_2\left(\underline{y}^{(i)}\right) \triangleq \\ &-\sum_{n=1}^{N} \log_2\left(D_{y-x_n}^{-\alpha_u} h_u G\sigma^2 + (R^*)\left(\sigma^2+\beta P_n^{UAV}\right) h_g g D_{x_n-z_n}^{-\alpha_g}\right. \\ &\left.+P_n^{UAV} D_{y-z_n}^{-\alpha_d} D_{y-x_n}^{-\alpha_u} h_d h_u G^2\right) \\ &+\sum_{n=1}^{N} \log_2\left(D_{y^{(i)}-x_n}^{-\alpha_u} h_u G\sigma^2 + (R^*)\left(\sigma^2+\beta P_n^{UAV}\right) h_g g D_{x_n-z_n}^{-\alpha_g}\right) \\ &+\sum_{n=1}^{N} \frac{-G\sigma^2\alpha_u\left(\underline{y}^{(i)} - \underline{x}\right) h_u D_{y^{(i)}-x_n}^{-\alpha_u-2}\left(\underline{y} - \underline{y}^{(i)}\right)\Big/\ln 2}{D_{y^{(i)}-x_n}^{-\alpha_u} h_u G\sigma^2 + (R^*)\left(\sigma^2+\beta P_n^{UAV}\right) h_g g D_{x_n-z_n}^{-\alpha_g}}. \end{aligned} \tag{15}$$

Then, we solve the optimization problem (16):

$$\underline{y}^{(i+1)} = \arg\min_{\underline{y}} \widehat{g}_2\left(\underline{y}^{(i)}\right). \tag{16}$$

Subsequently, we set $i = i+1$. This procedure is repeated until the convergence or for a predefined number of iterations. This procedure is presented in Algorithm 2. As can be seen from Eq. (15), if the locations of users change, the location of FD-UAV is updated by Algorithm 2 in few iterations and is fixed until network changes. We should notice that the major complexity of Algorithm 2 lies in solving (16) and the complexity of solving (16) by using the standard interior point method is $\mathcal{O}(8I_l)$ [27] where I_l denotes the total number of iterations of Algorithm 2.

Algorithm 2: Optimizing location of FD-UAV

1 Initialize $\underline{y}^{(0)}$ and set $i = 0$ (iteration number).
2 **Repeat**
3 Define an auxiliary function $\widehat{g}_2\left(\underline{y}^{(i)}\right)$ as (15).
4 Solve the optimization problem (16).
5 $i \leftarrow i+1$
6 **Until** the sequence $\left\{\widehat{g}_2\left(\underline{y}^{(i)}\right)\right\}$ converges.

For jointly optimizing the FD-UAV transmission power and location, we propose an iterative algorithm. In the first step, we set the initial values for FD-UAV transmission power in each channel and FD-UAV location. In the second step, we optimize FD-UAV power transmission using Algorithm

1 and in the third step, we optimize the location of FD-UAV using Algorithm 2 by considering optimized value of FD-UAV transmission power. After that, we update FD-UAV location and again optimize FD-UAV transmission power. In the above iterative method, the error which is defined as the difference between current and previous values of the optimization variable is calculated in each iteration and when the value of error is less than a predefined threshold, the algorithm converges, otherwise, it continues for a predefined number of iterations. The proposed iterative algorithm is represented in Algorithm 3. The computation complexity of Algorithm 3 lies in solving Algorithm 1 and Algorithm 2. Hence, the complexity of Algorithm 3 can be presented by $\mathcal{O}(I_{iter}(I_p N^3 + 8I_l))$ where N is the number of users, I_p, I_l and I_{iter} denote the number of iterations of Algorithms 1, 2 and 3, respectively. In addition, optimality of proposed algorithm is presented in Appendix C.

Algorithm 3: Proposed iterative algorithm

Initialize $P_n^{UAV(0)}$, $\underline{y}^{(0)}$ and set $j = 0$ (iteration number).
Repeat
    $P_n^{UAV(j+1)} \leftarrow$ Solving optimization problem using Algorithm 1 by $P_n^{UAV(j)}$ and $\underline{y}^{(j)}$.
    $\underline{y}^{(j+1)} \leftarrow$ Solving optimization problem using Algorithm 2 by $P_n^{UAV(j+1)}$ and $\underline{y}^{(j)}$.
    Update H_0 the altitude of FD-UAV using Eq. (8).
    $j \leftarrow j + 1$
Until converges.

IV. Simulation Results

The performance of the proposed system and resource allocation algorithm is evaluated bt performing several simulations. The network consists of $N = 20$ UL users and $N = 20$ DL users scattered in a square area with the dimension of $100 \times 100 (m^2)$. We consider the altitude of FD-UAV is bounded between $50m$ and $500m$. We set $\Theta_0 = \pi/4$, $w = 15MHz$, $\sigma_N = -65dB$, $\sigma_I = 0.1\sigma_N$, $\beta = -90dB$, $R_{min} = 20Kbits/s$ and $G_0 = 2.2846$. In addition, we assume that the height of ground BS is $30m$. To show the effectiveness of proposed scenario (labeled as 'FDUAV'), we compare the results of proposed system with these scenarios: UAV with HD communication used in [21] ('HDUAV'), ground BS equipped with FD communication used in [22] ('FDGBS') and ground BS with HD communication ('HDGBS'). The simulation results are averaged for 1000 different random realizations.

One of the most serious challenges of FD systems is SIC. In this scenario, we investigate the effect of imperfect SIC on DL sum-rate. As Fig. 2 indicates, if SIC performs perfectly ($\beta = -110dB$), the DL sum-rate is about twice of that in HD mode. However, if SIC is performed imperfectly, the DL sum-rate decreases until the performance of FD and HD modes are the same ($\beta = -50dB$ for FD-UAV and $\beta = -80dB$ for FD ground BS). After these points, HD mode outperforms FD mode.

The effect of half-power beamwidth on the DL sum-rate is investigated in Fig. 3. As expected, half-power beamwidth

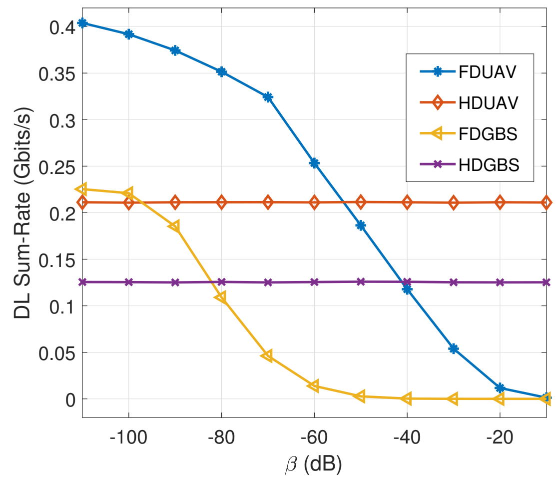

Fig. 2. DL Sum-Rate variations with respect to SIC factor (β).

does not affect DL sum-rate of ground BS and the value of DL sum-rate is fixed for all values of half-power beamwidth. By increasing half-power beamwidth, DL sum-rate of FD-UAV increases rapidly until about 15^o and after that point, DL sum-rate increases slowly. The reason is, by increasing half-power beamwidth, more users are covered by FD-UAV and DL sum-rate increases until a situation in which all users are covered by FD-UAV. DL sum-rate reaches its maximum value on 70^o, because after 70^o, almost all users are in the coverage of FD-UAV and by increasing half-power beamwidth, antenna gain decreases while the number of users is fixed and then, DL sum-rate decreases, consequently. In addition, FD-UAV and FD ground BS achieve more DL sum-rate in comparison with their HD counterparts.

The effect of maximum transmit power of both aerial and ground BSs on DL sum-rate is investigated in Fig. 4. By increasing the maximum transmit power of UAV, at first DL sum-rate increases rapidly, however for higher values of maximum power, DL sum-rate does not change considerably

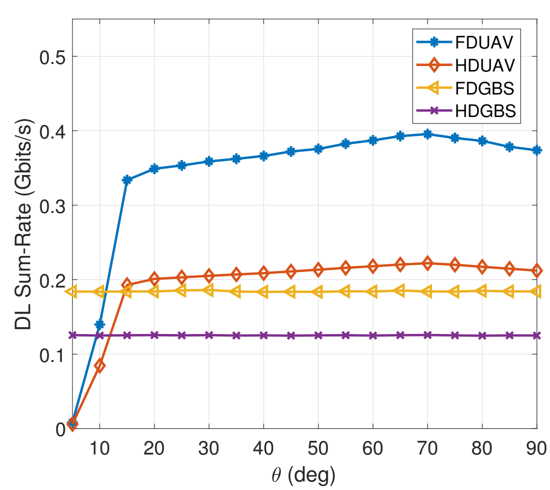

Fig. 3. DL Sum-Rate variations with respect to half-power beamwidth (θ).

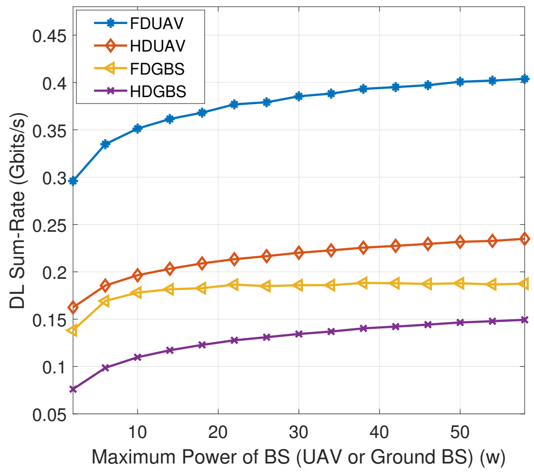

Fig. 4. DL Sum-Rate variations with respect to the maximum transmit power of ground and aerial BS.

and is almost fixed. As expected, by applying SIC, FD modes outperform HD modes and UAV outperforms ground BS.

In this scenario, we assume that the number of users is fixed ($N = 20$) and then we increase the cell dimension. Results are depicted in Fig. 5. From simulation results it can be seen that by increasing the cell dimension, FD modes are affected more than HD modes. Fig. 5 indicates that DL sum-rate of HD-UAV and HD ground BS decrease slightly, because of path-loss effect, however, DL sum-rate of FD-UAV and FD ground BS change, considerably. For small values of cell dimension, by increasing the cell dimension, interference decreases and hence, DL sum-rate of FD-UAV and FD ground BS increase until about $60m$ of cell dimension. After that point, DL sum-rate of FD modes decrease due to the path-loss effect. It can be seen that FD mode does not outperform HD mode in all cases; for some values of cell dimension, HD ground BS outperforms FD ground BS. Moreover, in almost all cases, FD-UAV and HD-UAV outperform ground BS because of SIC factor and dominant LOS connection.

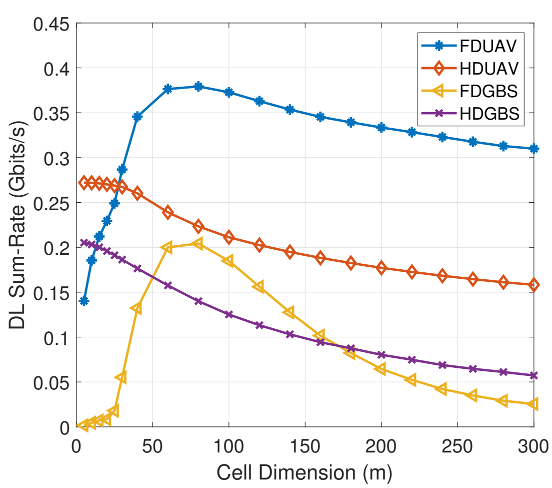

Fig. 5. DL Sum-Rate variations with respect to cell dimension with fixed number of users.

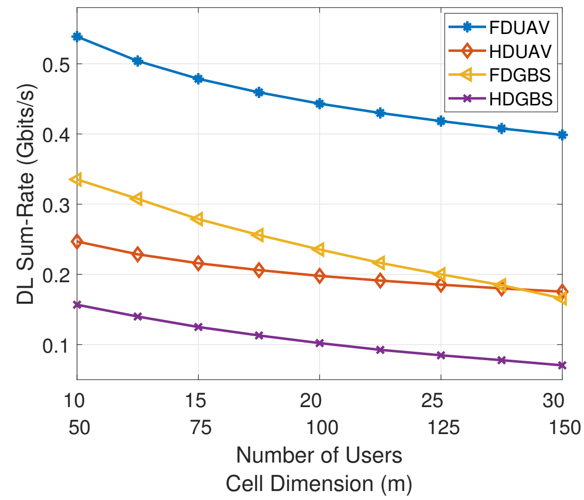

Fig. 6. DL Sum-Rate variations with respect to cell dimension and number of users.

Now we have fixed the density of users in the cell and investigate the effect of increasing cell dimension in Fig. 6. This figure indicates that by increasing cell dimension and the number of users, DL sum-rate decreases, because the distance between the transmitter and receiver increases while the BS maximum transmit power is fixed, therefore, the DL sum-rate decreases.

In Fig. 7 we investigate the effect of minimal rate demand as QoS factor on DL sum-rate. As expected, the minimal rate demand can not affect HD modes, but by increasing it, FD-UAV and FD ground BS receive more interference and DL sum-rate decreases. FD ground BS is affected more than FD-UAV because FD ground BS is closer to users in comparison with FD-UAV, therefore, it receives more interference from UL users.

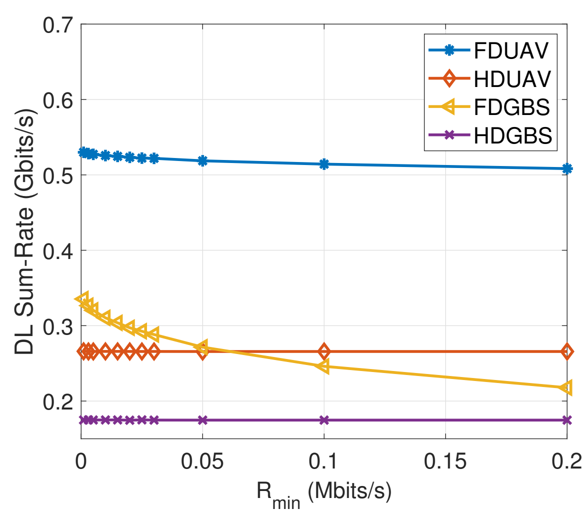

Fig. 7. DL Sum-Rate variations with respect to minimal rate demand.

V. Conclusion

In this paper, we considered a FD-UAV as an aerial BS with imperfect SIC to serve UL and DL users, simultaneously. In oder to optimize the performance of the network, we maximized DL sum-rate whilst guaranteeing a certain minimum requirement for UL transmission rate, by jointly optimizing the transmission power of users, FD-UAV transmission power and location. The optimization problem is non-convex, hence, we proposed an iterative method by exploiting D.C. programming to solve the problem. The proposed system model and Algorithms are simulated to evaluate and compare the performance of FD-UAV with ground BS to show the effectiveness of the proposed FD-UAV as aerial BS. In addition, simulation results confirmed that FD-UAV doubles the DL sum-rate when SIC is performed perfectly, while, when SIC is performed imperfectly, the amount of SIC factor can affect the network performance, considerably and in some cases, HD transmission outperforms FD one, because of SIC factor. Moreover, simulation results show two trade-offs, a trade-off between HD mode and FD mode, and a performance trade-off between aerial BS and ground BS in order to optimize the performance of a cell with maximum DL sum-rate considering a QoS constraint for UL transmission rate. The results of this study shows that in general, FD-UAV can effectively be used in next generation communication systems.

Appendix A
Feasibility of Problem (10)

We investigate feasibility of problem (10) by employing the feasibility checking problem [28]. To do this, we minimize FD-UAV transmit power subject to constraints (10b) and (10d). Problem (10) is infeasible if the minimal sum power of FD-UAV is larger than P_{max}^{UAV}. Assuming that P_n^{UAV*} is the minimal value of P_n^{UAV} according to (10b), the feasibility checking problem is equivalent to obtain the minimum value v^* of $\sum_{n=1}^{N} P_n^{UAV}$ assuming $P_n^{UE} = 0$, $H_0 = H_L$, and constraints are satisfied. The problem of sum power minimization can be solved by an exhaustive search. With fixed $\underline{y}$, we obtain the optimal transmit power of users via the interior point method. Then, we obtain the optimal value of $\underline{y}$ via the two dimensional exhaustive search. Consequently, problem (10) is feasible if and only if $P_{max}^{UAV} \geqslant v^*$.

Appendix B
Proof Of Lemma 1

We briefly prove Lemma 1 using contradiction method. Assume that the optimal solution of problem (10) is (P_n^{UAV*}, P_n^{UE*}). We can construct a new solution (P_n^{UAV+}, P_n^{UE+}) such that

$$\begin{aligned} P_n^{UAV+} &= \varepsilon P_n^{UAV*} \\ P_n^{UE+} &= \varepsilon P_n^{UE*} \end{aligned} \tag{17}$$

with $\varepsilon > 1$.

The solution (P_n^{UAV+}, P_n^{UE+}) is feasible but with larger objective value, which contradicts that the solution (P_n^{UAV*}, P_n^{UE*}) is optimal. It means that if the power does not reach the maximum value, we can scale up the power and the objective function can be increased. Lemma 1 is proved.

Appendix C
Optimality of Proposed Algorithm

As we mentioned before, the proposed method reaches a locally optimal solution. Lemma 2 can be written from Proposition 3 in [29] as follows:

Lemma 2: *Assume that $\mathcal{F}$ be a maximization problem with differentiable objective function $f_0(x)$ and constraints $f_i(x) \geqslant 0, i = 0, 1, ..., I$ with a compact feasible set. Moreover, consider $\mathcal{G}_|$ as a maximization problem with differentiable objective $g_{0,j}(x)$ and constraints $g_{i,j}(x) \geqslant 0, i = 0, 1, ..., I$ with a compact feasible set and optimal solution x_j^*. Assume that $g_{i,j}(.)$ satisfies the following properties for all values of i and j:*

- $g_{i,j}(x) \leqslant f_i(x) \forall x$
- $g_{i,j}(x_{j-1}^*) = f_i(x_{j-1}^*)$.

The sequence $\{f_0(x_j^*)\}$ is monotonically increasing and converges to a finite limit g. Then, assume $\nabla g_{i,j}(x_{j-1}^*) = \nabla f_i(x_{j-1}^*)$. Then, under suitable constraints qualifications, every limit point of $\{x\}_j$ that achieves the objective value g, fulfills the Karush-Kuhn-Tucker (KKT) conditions of the original problem $\mathcal{F}$ [29].

The first order Taylor's series is considered as a sequence of approximate problem, according to Lemma 2, a sequence of feasible points x_j can be generated that monotonically increases the value of the original objective f_0 and converges to a locally optimal solution.

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